

Stokes Inversion Techniques: Recent Advances and New Challenges

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Abstract. Inversion techniques (ITs) allow us to infer the magnetic, dynamic, and thermal properties of the solar atmosphere from polarization line profiles. In recent years, major progress has come from the application of ITs to state-of-the-art observations. This paper summarizes the main results achieved both in the photosphere and in the chromosphere. It also discusses the challenges facing ITs in the near future. Understanding the limitations of spectral lines, implementing more complex atmospheric models, and devising efficient strategies of data analysis for upcoming ground-based and space-borne instruments, are among the most important issues that need to be addressed. It is argued that proper interpretations of diffraction-limited Stokes profiles will not be possible without accounting for gradients of the atmospheric parameters along the line of sight. The feasibility of determining gradients in real time from space-borne observations is examined.

1. Introduction

We derive information on the physical properties of the solar atmosphere by interpreting the polarization profiles of spectral lines. Extracting this information is not easy, because the observed profiles depend on the atmospheric parameters in a highly non-linear manner through the absorption matrix and the source function vector. To solve the problem, least-squares inversion techniques (ITs) based on analytical or numerical solutions of the radiative transfer equation were developed in the past. These methods compare the observed Stokes profiles with synthetic profiles emerging from an initial guess model atmosphere. The misfit is used to modify the atmospheric parameters until the synthetic profiles match the observed ones. This yields a model atmosphere capable of explaining the measurements, within the assumptions and limitations of the model.

The first ITs were proposed by Harvey, Livingston, & Slaughter (1972) and Auer, House, & Heasley (1977). Many other codes have been developed since then (cf. Table 1 in del Toro Iniesta 2003). Today we have an IT for almost any application we may be interested in: LTE or non-LTE line formation, one-component or multi-component model atmospheres, photospheric or chromospheric lines, etc. These codes have been used intensively to study the magnetism of the solar atmosphere, and now they are essential tools for the analysis of spectro-polarimetric measurements.

This paper concentrates on recent achievements and future challenges of ITs. Additional information on ITs can be found in the reviews by del Toro Iniesta & Ruiz Cobo (1996), Socas-Navarro (2001), and del Toro Iniesta (2003).

2. Recent Advances

There have been no significant improvements of classical least-squares ITs in recent years: no new algorithms have appeared, and existing codes have not been optimized for speed. However, the experience accumulated has been used to develop new codes for specific purposes. The complexity of both atmospheric and line-formation models has also increased. For example, a few years ago the most sophisticated inversions of Stokes profiles from sunspots were based on one-component models with gradients of the physical parameters (Westendorp Plaza et al. 2001), while two-component inversions are now performed on a routine basis (Bellot Rubio, Balthasar, & Collados 2004; Borrero et al. 2004). Even more complex models are necessary to explain the net circular polarization (NCP) of spectral lines emerging from sunspot penumbrae. Sánchez Almeida (2005) used micro-structured magnetic atmospheres, assuming that the penumbra is formed by optically thin magnetic fibrils. Borrero et al. (2005) adopted an un-combed penumbral model with two different components representing inclined flux tubes embedded in a more vertical ambient field. Both models successfully reproduce the anomalous Stokes V profiles observed near the neutral line, for visible and infrared (IR) lines considered separately. The synthetic NCPs, however, are a bit smaller than the observed ones, implying that there is still room for improvement.

An important advance in the field has been the development of alternative methods for real-time analyses of large data sets. Other significant achievements have come from the application of classical ITs to state-of-the-art observations. These issues are examined in more detail in the next subsections.

2.1. Fast Inversion Codes

Conceptually, the simplest inversion is one that uses a look-up table. The idea is to create a database of synthetic Stokes profiles from a large number of known model atmospheres, and look for the profile in the database which is closest to the observed spectrum. The corresponding model is adopted as representative of the physical conditions of the atmosphere from which the profile emerged. Despite its simplicity, this method had seldom been put into practice until Rees et al. (2000) drew attention to Principal Component Analysis (PCA) as a means to accelerate the search in the look-up table. By virtue of PCA, the Stokes profiles can be expressed in terms of a few coefficients only. The comparison between observed and synthetic profiles is then performed very quickly, because the calculation does not involve the many wavelength points describing the full line profiles. PCA lies at the heart of several codes developed in the last years.

The database is the most critical component of any IT based on look-up tables, as its size increases dramatically with the number of free parameters. To keep this number to a minimum, only Milne-Eddington (ME) atmospheres have been used for PCA inversions of photospheric lines (e.g., Socas-Navarro, López Ariste, & Lites 2001). Even under ME conditions, the parameter space cannot be sampled very densely. The discrete nature of the database introduces numerical errors, and so PCA analyses are less accurate than least-squares ME inversions (e.g., Skumanich & Lites 1987). However, the method gives an idea of the quality of the fit in terms of the so-called PCA distance. When this

distance is large, the observed profile cannot be associated with any profile in the database, making it possible to identify pixels that deserve closer attention.

A nice feature of PCA inversions is that the search algorithm is independent of the database. The synthesis of Stokes profiles may be very time-consuming, but the inversion will always be fast. This opens the door to the analysis of lines for which atomic polarization effects are important. López Ariste & Casini (2002) have developed a PCA inversion code to exploit the diagnostic potential of the Hanle effect in the He I D₃ line at 587.6 nm. The database is created using a line formation code which solves the statistical equilibrium of a He atom with 5 terms, in the presence of magnetic fields. Coherences between fine-structure levels within each atomic term are accounted for to treat the Zeeman and Hanle regimes, including level crossing (incomplete Paschen-Back effect). This code has been applied to prominences (López Ariste & Casini 2003; Casini et al. 2003) and spicules (López Ariste & Casini 2005).

The speed of PCA inversions makes it possible to handle large amounts of data in real time. Since 2004, PCA is used at the French-Italian THEMIS telescope to derive vector magnetic fields from MTR measurements of the Fe I 630 nm lines (López Ariste et al. 2006). Full maps are inverted in about 10 min, which is more or less the time needed to take the observations. At the telescope, PCA is very useful for quick-look analyses, allowing one to select interesting targets or to continue the observation of interesting regions. While real-time analyses are appealing, it is important to keep in mind their limitations. In most cases, a proper interpretation of the observations will require more sophisticated ITs, which however can use the results of PCA methods as initial guesses.

Another promising technique explored in recent years is Stokes inversion based on artificial neural networks (ANNs). The idea was introduced by Carroll & Staude (2001) and developed by Socas-Navarro (2003, 2005a). Essentially, an ANN is an interpolation algorithm. One starts by setting up the structure of the network, i.e., the number of layers and the number of neurons in each layer. The input layer receives the observations (the Stokes profiles or a suitable combination thereof) and the last layer outputs the unknown atmospheric parameters. The ANN must be trained before applying it to real data. To this end, Stokes profiles synthesized using different ME atmospheres are presented to the ANN in order to find the synaptic weights and biases of the neurons that return the model parameters used to compute the profiles. The training process is very slow but, once accomplished, the ANN will invert a full map in a matter of seconds. Indeed, ANNs are the fastest ITs available nowadays. For the moment, however, they have not been used in any scientific application.

Several strategies have been explored to optimize the performance of ANNs. It seems that the best choice is to invert one parameter at a time with a dedicated ANN. Finding all atmospheric parameters with a single ANN is possible, but requires a larger number of neurons and the training process becomes very complicated.

Socas-Navarro (2005a) has shown that the mean field strengths inferred with the help of ANNs are reasonably accurate from a statistical point of view. On average they resemble those provided by ME inversions. However, the errors can be very large for individual pixels, as evidenced by the large r.m.s. uncertainties (Fig. 8 in that paper indicates an uncertainty of 0.3 kG for fields of 1.2 kG, i.e.,

a relative error of 25%; the error is even larger for weaker fields). This means that ANNs may be appropriate for quick-look analyses and other applications where high precision is not required. For detailed studies of physical processes, current ANNs seem not to be accurate enough.

A limitation of both PCA-based inversions and ANNs is the use of ME atmospheres, which precludes the determination of gradients of physical parameters from the observed profiles. It remains to be seen whether these methods can be modified in order to reliably recover gradients along the line of sight (LOS). As discussed in Sect. 3.3, gradients appear to be essential for the analysis of observations at very high spatial resolution.

2.2. Application of ITs to State-of-the-Art Observations

Major breakthroughs have come from the application of ITs to state-of-the-art observations, including spectro-polarimetry in the near IR, simultaneous observations of visible and IR lines, spectro-polarimetry of molecular lines, and observations at very high spatial resolution.

The development of polarimeters for the IR, most notably the Tenerife Infrared Polarimeter (TIP; Martínez Pillet et al. 1999), has opened a new window with lines that offer excellent magnetic sensitivity and chromospheric coverage. One example is the He I triplet at 1083 nm, which has become an essential tool to investigate the upper chromosphere. The formation of the triplet is complex and not really well understood. However, since the triplet lines are nearly optically thin, ME atmospheres provide a good description of their shapes. An inversion code specifically designed for He I 1083 nm, HELIX, was presented by Lagg et al. (2004). It is based on the Unno-Rachkovsky solution of the radiative transfer equation and includes an empirical treatment of the Hanle effect. Outside active regions, the linear polarization profiles of He I 1080.3 nm show the signatures of the Hanle effect, which needs to be taken into account for correct retrievals of vector magnetic fields (Trujillo Bueno et al. 2002). HELIX implements the PIKAIA genetic algorithm, rather than the more common Marquardt algorithm employed by other least-squares ITs. Using the magnetic information obtained with HELIX, Solanki et al. (2003) were able to trace individual coronal loops in an emerging flux region. They found upflows at the apex of the loops and downdrafts near the footpoints, which is what one expects for magnetic loops rising from deeper layers. Other applications of the code have been presented by Lagg (2005), Orozco Suárez, Lagg, & Solanki (2005), and Solanki et al. (2006).

Routine observations of the IR triplet of Ca II at 850 nm are now possible with the MTR mode of THEMIS and the Spectro-Polarimeter for INfrared and Optical Regions (SPINOR; Socas-Navarro et al. 2006a) mounted on the Dunn Solar Telescope (DST) of the National Solar Observatory at Sacramento Peak. The Ca IR triplet lines are excellent diagnostics of the chromosphere, with the advantage that their interpretation is much simpler than that of other chromospheric lines such as Ca II H, Ca II K, and H α . However, they still require non-LTE computations. Non-LTE inversions of the Ca IR triplet lines observed with SPINOR have been presented by Socas-Navarro (2005b) and Socas-Navarro et al. (2006b). Although these analyses are very demanding in terms of computational resources, they hold great promise for quantitative diagnostics of the thermal and magnetic structure of the solar chromosphere.

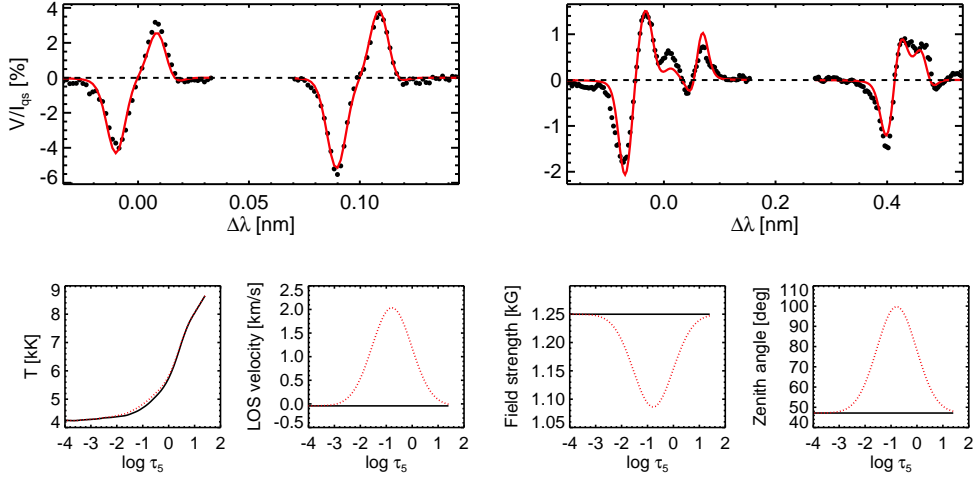


Figure 1. *Top:* Stokes V profiles of the pair of Fe I lines at 630 nm (*left*) and the Fe I lines at 1565 nm (*right*) observed simultaneously with POLIS and TIP in the limb-side penumbra of AR 10425, near the neutral line. Dots indicate the observations, solid the best-fit profiles resulting from a simultaneous inversion of the data. *Bottom:* Uncombed penumbral model inferred from the inversion. From left to right: temperature, LOS velocity, field strength, and field inclination in the background (solid) and the flux-tube (dashed) components (from Beck, Bellot Rubio, & Schlichenmaier, in preparation).

Simultaneous observations of visible and IR lines improve the accuracy of inversion results due to their different sensitivities to the various atmospheric parameters (Cabrera Solana, Bellot Rubio, & del Toro Iniesta 2005). Several instruments are capable of such observations, including TIP and POLIS (Polarimetric Littrow Spectrograph; Beck et al. 2005) at the German VTT in Tenerife, and SPINOR at the DST. Figure 1 shows examples of Stokes V profiles of the Fe I lines at 630.15 nm, 630.25 nm, 1564.8 nm, and 1565.2 nm observed in the penumbra of AR 10425 near the neutral line. These profiles were taken strictly simultaneously with TIP and POLIS on August 9, 2003. Both the visible and IR lines exhibit large asymmetries and even pathological shapes, suggesting the presence of two magnetic components in the resolution element. We have carried out an analysis of these profiles in terms of an uncombed penumbral model using the code described by Bellot Rubio (2003). The best-fit profiles from the simultaneous inversion are represented by the solid lines. The quality of the fits is certainly remarkable, but it should be stressed that even better fits are achieved from the inversion of only the visible or the IR lines. Indeed, fitting both sets of lines simultaneously is much more difficult, because a model atmosphere appropriate for the visible lines may not be appropriate for the IR lines, and vice versa. Measurements in two or more spectral regions thus constrain the range of acceptable solutions. The lower panels of Fig. 1 show the uncombed model resulting from the inversion (Beck, Bellot Rubio, & Schlichenmaier, in preparation). The dashed lines represent a penumbral flux tube with larger LOS velocities than the background atmosphere, indicated by the solid lines. The field is weaker and more horizontal in the tube. These inversions confirm

that the uncombed model is able to explain the observed shapes of both visible and IR lines. At the same time, they allow us to determine the position and width of the penumbral tubes, which is not easy from visible or IR lines alone. Other examples of the analysis of simultaneous measurements in the visible and IR are given by Bellot Rubio & Beck (2005) and Beck et al. (2006).

The new polarimeters have also extended our capabilities to observe molecular lines, providing increased thermal sensitivity. Molecular lines are mostly seen in sunspot umbrae, because higher temperatures dissociate the parent molecules. Usually, they show smaller polarization signals than atomic lines. Two codes capable of inverting molecular lines are SPINOR (Frutiger & Solanki 1998) and the one developed by Asensio Ramos (2004). SPINOR has been used to analyze the OH lines at 1565.2 nm and 1565.3 nm, improving the determination of umbral temperatures (Mathew et al. 2003). The second code has been employed to invert the CN lines at 1542 nm (Asensio Ramos, Trujillo Bueno, & Collados 2005). These lines are very interesting because in the umbra they show large linear polarization signals but very small Stokes V signals, just the opposite behavior of atomic lines.

Finally, major progress has come from the application of ITs to high spatial resolution spectroscopic and spectro-polarimetric measurements. The main advantage of high spatial resolution is that the results are less dependent on filling factor issues. An example of the inversion of high spatial resolution Stokes profiles is the work of Socas-Navarro et al. (2004), who derived the magnetic and thermal properties of umbral dots from observations taken with the La Palma Stokes Polarimeter (Martínez Pillet et al. 1999) at a resolution of about $0''.7$. Another promising type of measurements are those provided by Fabry-Pérot interferometers such as the Interferometric Bidimensional Spectrometer (IBIS; Cavallini 2006) and the TElecentric SOLar Spectrometer (TESOS; Kentischer et al. 1998), which has recently been equipped with the KIS/IAA Visible Imaging Polarimeter (VIP; Bellot Rubio et al. 2006). Combined with adaptive optics systems, these instruments perform 2D vector spectro-polarimetry at high spatial, spectral, and temporal resolutions, which is necessary to investigate fast processes in large fields of view. An example of the inversion of 2D spectroscopic measurements with TESOS is the derivation of the thermal and kinematic properties of a sunspot penumbra at different heights in the atmosphere (Bellot Rubio, Schlichenmaier, & Tritschler 2006; see also Bellot Rubio 2004). The angular resolution of these observations is $0''.5$.

In the future, significant progress may come from the routine inversion of lines showing hyperfine structure, such as Mn I 553.77 nm and 874.09 nm (López Ariste, Tomczyk, & Casini 2002). These lines exhibit sign reversals in the core of Stokes V and multiple peaks in Stokes Q and U for weak fields. Interestingly, the shape of the anomalies depends on the magnetic field strength, rather than on the magnetic flux. Such an unusual behavior can be used to investigate the magnetism of the quiet Sun. In fact, from the shape of the observed profiles it would be possible to determine directly the strength of the magnetic field, even in the weak field regime. To exploit the diagnostic potential of these lines, however, it is necessary to implement the appropriate Zeeman patterns in existing ITs and to lower the noise level of current observations, which is barely enough to detect the subtle signatures induced by hyperfine structure.

3. Challenges

ITs have proven to be essential tools to characterize the properties of the solar atmosphere. Their application to high precision spectro-polarimetric measurements, however, has started to raise concerns on the limitations of some spectral lines. This is an important problem that deserves further investigation. Other challenges facing ITs in the near future include the implementation of more realistic model atmospheres and the development of strategies for the analysis of the large amounts of data to be delivered by upcoming instruments.

3.1. Limitations of Spectral Lines

Martínez González, Collados, & Ruiz Cobo (2006) have shown that it is possible to fit a given set of Stokes profiles of the pair of Fe I lines at 630 nm with very different field strengths by slightly changing the temperature stratification and the microturbulent velocity, for typical conditions of quiet Sun internetwork regions. The reason is the different formation height of the two lines. This quite unexpected result suggests that one cannot determine reliable internetwork field strengths from Fe I 630.15 nm and 630.25 nm without a prior knowledge of the actual temperature stratification. Other lines such as Fe I 524.71 nm and Fe I 525.02 nm could provide the necessary information.

We have found a similar problem with the Fe I 630 nm lines even in the umbra, where the strong field regime applies. More specifically, we have detected a cross-talk problem between the stray light coefficient, the temperature, and the magnetic field strength and inclination (see Cabrera Solana et al. 2006). The results of one-component inversions of umbral profiles with the stray light contamination as a free parameter do differ from those in which the stray light factor is fixed to the value inferred from a simultaneous inversion of visible and IR lines. With a mere difference of 7% in the stray light coefficient, the temperatures at $\tau_5 = 1$ from the two inversions may differ by up to 150 K, and the field strength by about 200 G. The fits are equally good in both cases, so it is not possible to decide which inversion is better. It appears that the relatively small Zeeman splitting of the Fe I 630 nm lines does not allow to clearly distinguish between larger stray light factors and weaker fields, which produces cross-talk among the various atmospheric parameters.

Given these concerns, more detailed studies of the limitations of visible and IR lines seem warranted, for a better understanding of the results obtained from them. To minimize the risk of cross-talk problems in the inversion, it is desirable to use simultaneous measurements in different spectral ranges. This will require modifications of current inversion codes to account for different stray light levels and different instrumental profiles in the different spectral ranges.

3.2. Implementation of More Realistic Atmospheric Models

The new observational capabilities, in particular the availability of simultaneous observations of visible and IR lines, offer us a unique opportunity to increase the realism of the atmospheric models implemented in existing ITs. The need for better models is indicated by the small (sometimes systematic) residuals observed in inversions of profiles emerging from complex magnetic structures.

As an example, consider the uncombed penumbral model. Right now we use two different lines of sight to represent the background and flux-tube atmospheres (cf. Bellot Rubio 2003; Borrero et al. 2005), but this is a very simplistic approximation. The ambient field lines have to wrap around the flux tube, hence the properties of the background cannot be the same far from the tube and close to it. This may have important consequences for the generation of asymmetrical Stokes profiles. In much the same way, the flux tube is not always at the same height within the resolution element, because the magnetic field is not exactly horizontal. Therefore, different rays will find the tube at different heights. Finally, lines of sight crossing the center of the tube sense the properties of the tube over a larger optical-depth range than lines of sight crossing the tube at a distance from its axis. Neither of these effects are modeled by current inversion codes. Probably, the subtle differences between observed and best-fit profiles (cf. Fig. 1) would disappear with a more complex treatment of the magnetic topology of sunspot penumbrae.

3.3. Analysis of Data from Next-Generation Instruments

Stokes polarimetry at the diffraction limit is needed to study the physical processes occurring in the solar atmosphere at their intrinsic spatial scales. We are pushing our technological capabilities to the limit by building grating spectropolarimeters and filter magnetographs for diffraction-limited observations. On the ground, examples of already operational or upcoming state-of-the-art instruments include TIP, POLIS, DLSP, SPINOR, IBIS and TESOS+VIP. Among space-borne instruments we have the spectro-polarimeter and filter polarimeter onboard Solar-B, IMaX onboard SUNRISE, HMI onboard SDO, and VIM onboard Solar Orbiter.

These instruments will deliver data of unprecedented quality in terms of spatial and spectral resolution. We hope to further our understanding of the solar magnetism with them. However, the success of this endeavor will critically depend on our ability to extract in an appropriate way the information contained in the observations. We do not only want to investigate the morphology and temporal evolution of the various solar structures from diffraction-limited images, but also to derive their magnetic and kinematic properties accurately using polarization measurements. Reliable determinations of vector magnetic fields call for least-squares inversions. The problem is the enormous data flows expected: classical least-squares ITs are considered to be too slow for real-time analyses of the observations. This is the reason why it is taken for granted that the most sophisticated inversions of the data will be based on ME models. The question naturally arises as to whether or not ME atmospheres are appropriate for the interpretation of Stokes measurements at very high spatial resolution.

To shed some light on this issue, I have used the MHD simulations of Vögler et al. (2005) to synthesize the Stokes profiles of the IMaX line (Fe I 525.06 nm) emerging from a typical magnetic concentration in an intergranular lane. The atmospheric parameters needed for the calculation have been taken from a simulation run with average magnetic flux density of 140 G. Figure 2 displays the atmospheric stratifications and the corresponding Stokes profiles at 0".1 resolution (solid lines). The dotted lines show the results of a ME inversion of the synthetic profiles. As can be seen, the fits to Stokes I and V are not very

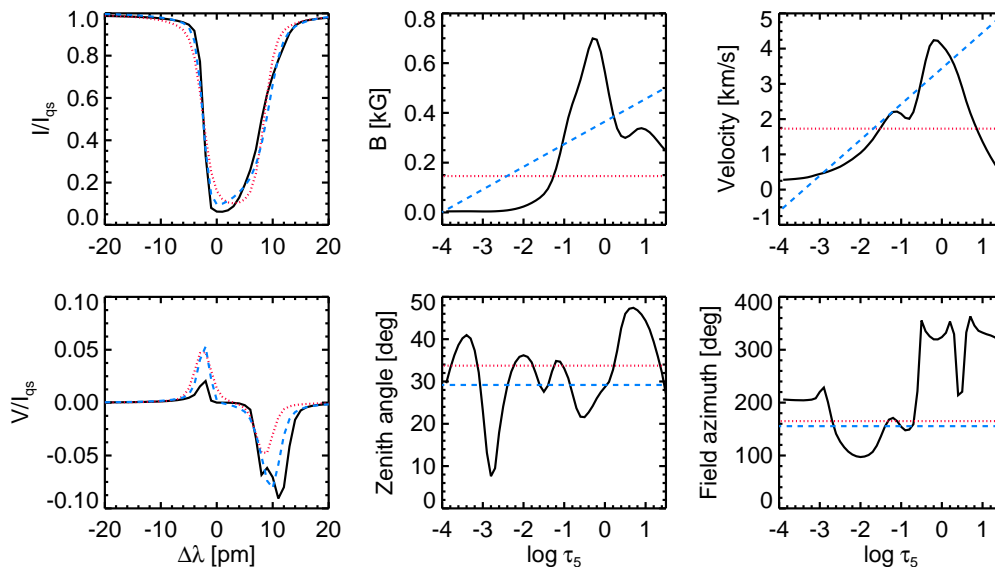


Figure 2. *Left:* High spatial resolution Stokes I and V profiles of Fe I 525.06 nm emerging from an intergranular lane as computed from MHD simulations (solid). Dotted and dashed lines represent the best-fit profiles from a ME inversion and a SIR inversion with gradients, respectively. *Middle and right:* Stratifications of atmospheric parameters used for the spectral synthesis (solid). The results of the ME inversion and the SIR inversion are given by the dotted and dashed lines, respectively.

successful, due to the extreme asymmetries of the profiles. The atmospheric parameters inferred from the ME inversion are some kind of average of the real stratifications, but the significance and usefulness of these average values are questionable when the parameters feature such strong variations along the LOS. An analysis of the same profiles with SIR (Ruiz Cobo & del Toro Iniesta 1992) allowing for vertical gradients of field strength and velocity yields much better fits to Stokes I and V (dashed lines). Although the fits can still be improved, the important point is that this simple SIR inversion is able to recover the gradients of field strength and velocity with fewer free parameters than the ME inversion (8 as opposed to 9). This additional information could be essential to understand many physical processes, so it is important to have it.

Present-day computing resources are sufficient to determine gradients from the high spatial resolution observations delivered by *grating instruments* such as POLIS and the Solar-B spectro-polarimeter (Solar-B/SP; Lites, Elmore, & Stander 2001). A SIR inversion of the four Stokes profiles of 2 spectral lines (10 free parameters, 135 wavelength points, model atmosphere discretized in 41 grid points) takes 0.7s on a dual Xeon workstation running at 2.8GHz. Optimizing the code, a cadence of 0.5s may easily be reached. The real-time analysis of a full POLIS slit (450 pixels in 10s) would then require 20 such workstations. The analysis of Solar-B/SP data (1000 pixels every 10s) would require 50 workstations. In both cases, the total cost would be a minor fraction of the cost of the instruments themselves.

The situation is rather different for vector magnetographs. These instruments measure only a few wavelength points, i.e., line profiles are not available. Probably, the most we can do with this kind of data is a full least-squares ME inversion.¹ An additional complication is that the data rates will be huge, much larger than those expected from grating instruments. For example, HMI will observe about 10^6 pixels every 80–120 s. To cope with such data flows, PCA methods and ANNs are being proposed as the only option to invert the observations in real time. We have already mentioned that on average the results of these methods coincide with those from ME inversions. However, since large errors occur for many individual pixels, it is clear that ME inversions would be preferable over PCA or ANN analyses.

But, how to perform ME inversions of vector magnetograph data at the required speed? The solution could be hardware inversion on Field Programmable Gate Arrays (FPGAs), which is about 10^3 times faster than software inversion depending on the frequency of the processor and the implementation of the algorithm. At the IAA, we are studying the feasibility of such an electronic inversion for the analysis of VIM data (Castillo Lorenzo et al. 2006). The first working prototype is expected to be ready by the end of 2007.

4. Summary

Inversion techniques (ITs) have become essential tools to investigate the magnetism of the solar atmosphere. Nowadays, they represent the best option to extract the information contained in high precision polarimetric measurements. The reliability and robustness of least-squares Stokes inversions have been confirmed many times with the help of numerical tests. Part of the community, however, is still concerned with uniqueness issues. These concerns will hopefully disappear with the implementation of more realistic model atmospheres.

During the last years, major progress in the field has resulted from the application of ITs to state-of-the-art observations. The advent of spectro-polarimeters for the near IR has represented a breakthrough, allowing the observation of atomic and molecular lines that provide increased magnetic and thermal sensitivity, and extended chromospheric coverage. The potential of simultaneous observations of visible and IR lines for precise diagnostics of solar magnetic fields has just started to be exploited. Visible and IR lines constrain the range of acceptable solutions, which is especially useful for the investigation of complex structures with different magnetic components and/or discontinuities along the LOS. Finally, we have begun to invert spectro-polarimetric observations at very high spatial resolution, with the aim of reaching the diffraction limit of current solar telescopes ($0''.1$ – $0''.2$). High spatial resolution allows to separate different magnetic components that might coexist side by side, thus facilitating the determination of their properties.

¹However, it remains to be seen whether vertical gradients can also be recovered from observations with limited wavelength sampling. Work in this direction is being done at the IAA in preparation for the analysis of data from IMaX and VIM (Orozco Suárez, Bellot Rubio, & del Toro Iniesta 2006).

The application of ITs to these observations is casting doubts on the capabilities of certain lines for investigating particular aspects of solar magnetism. A detailed study of the limitations of spectral lines, in particular the often used Fe I pair at 630 nm, seems necessary to clarify their range of usability. An obvious cure for any problem that might affect the observables is to invert visible and IR lines simultaneously. This will require modifications of current ITs to account for different instrumental effects in the different spectral ranges.

Perhaps the most important challenge facing ITs in the next years is the analysis of the enormous data sets expected from upcoming space-borne polarimeters. So far, the efforts have concentrated on the development of fast PCA-methods and ANNs for real-time inversions of the data. However, the unprecedented quality of these observations in terms of spectral and spatial resolution makes it necessary to explore the feasibility of more complex inversions capable of determining gradients of field strength and velocity along the LOS. Tests with numerical simulations demonstrate the importance of gradients to reproduce the very large asymmetries of the Stokes profiles expected at a resolution of $0''.1$ – $0''.2$. Current computational resources allow us to determine gradients from full line profiles observed with grating spectro-polarimeters such as the one onboard Solar-B, at a very reasonable cost. Gradients might also be recovered from high-resolution filtergraph observations if sufficient wavelength points are available. Interestingly, real-time ME inversions of data with limited wavelength sampling seem possible using FPGAs. The feasibility of such electronic ME inversions needs to be assessed. At the same time, it is important to continue the development of PCA and ANN methods to provide the more complex ME inversions with good initial guesses.

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